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Research Department Report

EXPERIMENTS WITH THE HIVITS HDTV CONTRIBUTION CODEC

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Summary

As more and more programmes are made in high definition television (HDTV) formats, so the need to provide complete production facilities will increase. An important part of television production is the ability to transmit very high quality television signals over long distances for programme contribution purposes. For example, this may be from an outside broadcast unit to a television studio centre or a transatlantic satellite link for a live television interview.

The BBC Research Department, in collaboration with Thomson-CSF/LER and TRT, a French subsidiary of Philips, as part of the RACE HIVITS project, has participated in the construction of 140 Mbit/s contribution-quality bit-rate reduction codec for the transmission of digital HDTV. This Report describes the codec architecture, some of the problems that have arisen out of the necessity to perform parallel processing, results from buffer regulation optimisation experiments and results from the field trials conducted over satellite links.

The architecture of this equipment has been especially developed to allow the generation of an implementation-independent bit stream. The current equipment based on six conventional definition bit-rate reduction codecs working in parallel, will perform equally well with future generations of equipment based on fewer processing units operating in parallel. Indeed, the output bit stream is equivalent to a suitably scaled version of the current ETSI and CMTT standards for the coding of conventional definition television.

Index terms: *RACE; HIVITS; bit-rate reduction; digital video signals; high definition television; buffer regulation; source coding; transform coding; DCT (discrete cosine transform)*

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1. INTRODUCTION

The BBC, together with Thomson and TRT as part of the RACE* HIVITS† project (No. 1018), has participated in the construction of a bit-rate reduction codec for digital HDTV. The codec is intended primarily for 'contribution' quality coding of HDTV signals at around 140 Mbit/s. Operation at lower bit rates (e.g. 70 Mbit/s) has also been demonstrated. The HDTV codec is based on the operation, in parallel, of six conventional definition (TV) bit-rate reduction coders and decoders with a dynamic sharing of bit rate between the individual codecs. The TV codecs conform closely with the new ETSI and CCIR Recommendations[1] for codecs operating at bit rates between 34 and 45 Mbit/s.

The codec architecture will be described, along with some of the associated problems of optimisation experiments carried out with the codec hardware. The hardware has been used on a number of occasions to provide live HDTV transmission via satellite (EUTELSAT-II F3).

It should be noted, that the techniques described are also applicable to the transmission of multiple TV services within a single channel in which there is a dynamic sharing of bit rate between the individual TV services; thus, a constant quality is maintained across all services.

2. CODEC ARCHITECTURE

The coder splits each field into horizontal stripes, each of 8 lines. Successive stripes of a field are processed by successive sub-coders and associated sub-decoders as illustrated in Fig. 1. This architecture can give a bit stream which is independent of the number of sub-coders (or sub-decoders) in parallel.

The methods adopted in the HIVITS codec for co-ordination and synchronisation of the individual sub-coders and decoders are described in the following Sections.

2.1 Sub-coders

Each sub-coder uses motion-compensated interframe prediction, the discrete cosine transform (DCT) and variable-length coding[2, 3] as defined for 34 - 45 Mbit/s coding in CCIR Recommendation 723. A block diagram of an individual sub-coder is given in Fig. 2 *(overleaf)*. The motion vector search area is +15/−16 pixels horizontally and +7/−8 field-lines vertically relative to the position of the current block. The motion vector between frames is measured to half-pixel accuracy. The search area contains pixels which have been processed in the previous frame by the sub-coder above and the sub-coder below. In order to have access to these, a connection is made from the output of the frame store of each sub-coder to the motion estimation and compensation circuitry of the sub-coder above and the sub-coder below, as indicated in Fig. 2. This can be done with simple interconnection between the codecs and with little modification to the circuits of a stand-alone conventional-definition codec.

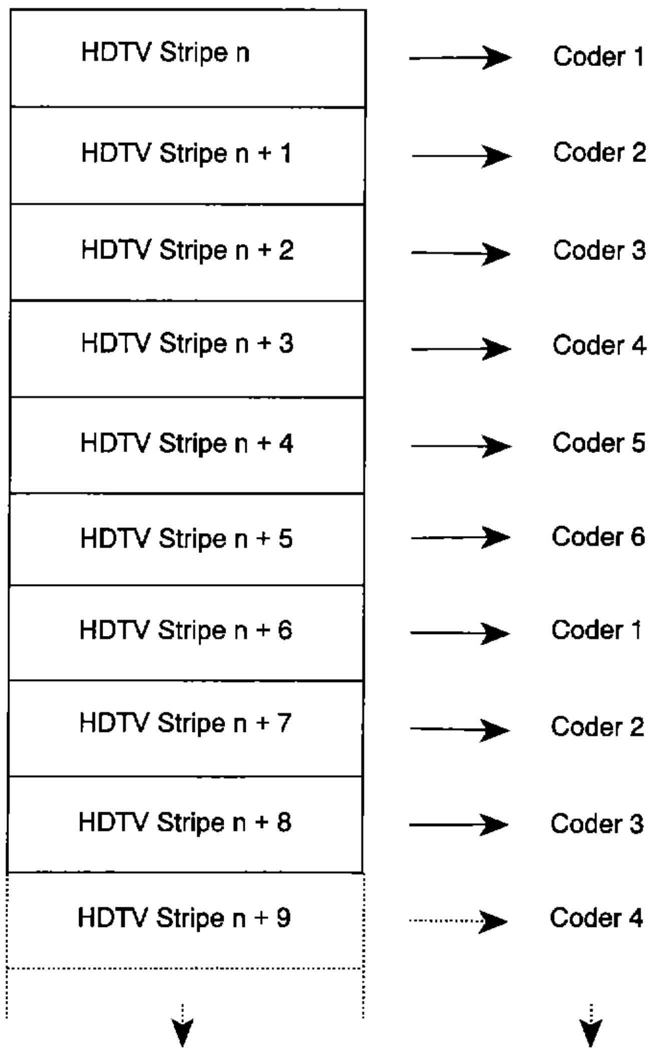

Fig. 1 - Illustration of stripe-based demultiplexing.

* Research into Advanced Communications in Europe.
† High Quality Video Telephone and HD (TV) Systems.

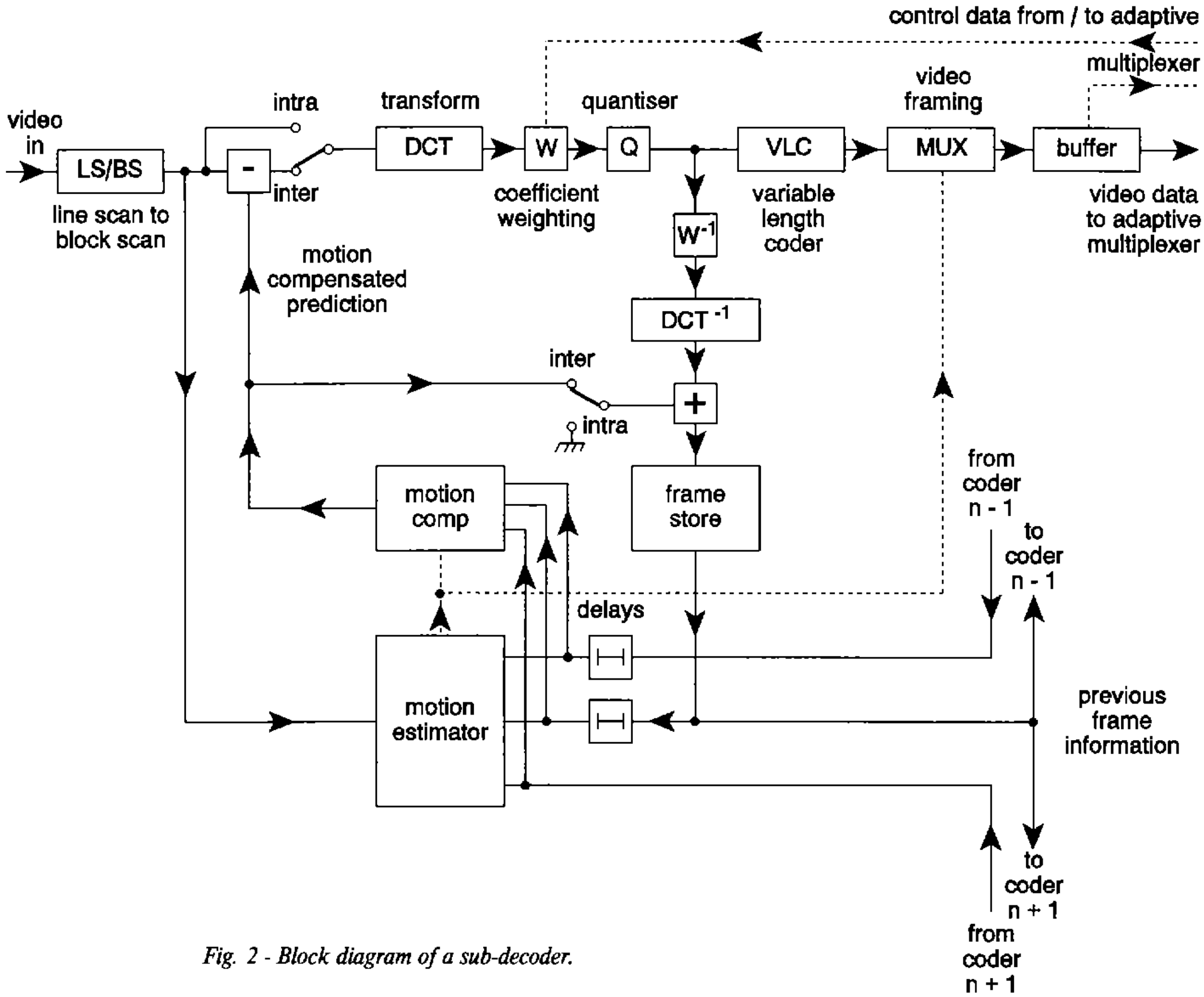

Fig. 2 - Block diagram of a sub-decoder.

Each sub-coder has its own individual sub-buffer store to smooth the data rate produced by its own variable-length coder. Each sub-buffer then sends one stripe's worth of information in turn to the transmission channel. Such a stripe-based multiplex is independent of the number of sub-coders in parallel and can be made to be equivalent to a single-loop coder operating at full HDTV rate with one output buffer. At the decoder, stripes of information are directed towards sub-decoders in turn. There could be any number of sub-decoders in parallel.

Forward error correction (double-interleaved RS 239,255) is applied to the video data as it is formed up into the 140 Mbit/s bit stream. The structure chosen for the 140 Mbit/s multiplex is based on a 138.240 Mbit/s TV container[4] for compatibility with future SDH (Synchronous Digital Hierarchy) transmission networks. The TV container is carried together with clock regeneration information within the standard 139.264 Mbit/s channel. The TV container includes a 2048 kbit/s channel for sound. In the case of the transmission of multiple TV services within a single channel, each sub-coder codes a separate service. The links between sub-coders to allow vertical motion compensation are therefore no longer required. Just as for HDTV, sub-coder buffers send data in sequence, one stripe at a time, to the transmission channel. Should a stripe from one sub-coder contain more bits than a stripe from another, then naturally its bit rate will be higher. By setting the quantiser step-size the same for all sub-coders and allowing the stripe lengths to vary, all TV services are coded at a uniform quality and their bit rates allocated dynamically. Steps must be taken to ensure that individual sub-coder and decoder buffers do not under- or overflow, but these steps are identical to those taken in the case of coding HDTV and are discussed in Sections 3, 4 and 5.

2.2 Sub-decoder synchronisation

In a standard 34 - 45 Mbit/s codec, the decoder contains a buffer store as an interface between

the fixed bit rate of the transmission channel and the variable bit rate required by the variable-length decoder. It can easily be shown that, when the transmission rate is fixed, the occupancy of this decoder buffer is complementary to the occupancy of the coder buffer. In order to ensure synchronisation of the coder and decoder buffers, the buffer occupancy of the coder buffer at a particular point in the picture is inserted into the video data stream; for example, after a field or stripe synchronisation word in the data. In addition, correct synchronisation of the two buffers fixes the precise delay between coder input and decoder output.

However, in the present case of parallel implementation, the bit rate per sub-codec is not constant but dependent on the amount of information present in each stripe. The buffer occupancies of the sub-coder and the corresponding sub-decoder buffer are, therefore, not complementary. In order to be able to synchronise each decoder, the buffer occupancy information in the standard bit stream is replaced, at the output of each sub-coder buffer, by coder time-base information. The decoder can then synchronise its own time-base such that the delay between coder input and decoder output is a known and fixed value.

The fact that individual coders can operate at different bit rates also adds to the difficulties of buffer regulation. Care must be taken to avoid instabilities and to ensure that decoder buffers do not overflow. The problems of buffer regulation will be dealt with more fully in the following section.

In addition to time-base information, each stripe of data carries a stripe number which enables the decoder to send each stripe of data in turn to the correct sub-decoder. This number is transmitted twice and also compared with a value estimated from the previous stripe number. If errors are such that a sub-decoder loses confidence that it has received a correct stripe (or has transmission errors within the stripe), then the decoder conceals the decoded output for that stripe using previous frame information.

3. BUFFER REGULATION

Buffer stores are required to adapt between the variable bit rate generated by the coding process (and the variable bit rate required by the decoding process) and the bit rate provided by the channel. The occupancy of the coder buffer is also used to regulate the quantisation step in order to control the average bit rate. With the current parallel architecture, individual sub-coders and decoders have their own buffers. Also, sub-coders and decoders operate at a bit rate which varies from stripe to stripe according to the characteristics of each part of the picture. In this case, the buffer regulation law should ensure constant quality across each sub-codec and also prevent individual coder or decoder buffer overflow/underflow.

In the current implementation, it is theoretically possible, with a specifically designed picture, for all the activity to occur in those parts of the picture processed by a single sub-codec. In this case, the full bit rate would be taken by that sub-coder. The corresponding sub-decoder buffer could then overflow. Section 5 explains how decoder buffer overflow is prevented, but this involves reducing the effective coder buffer size.

However, limiting the coder buffer size affects the regulation performance. This has led to the investigation of buffer regulation strategies, in order to optimise performance for a limited buffer size. Note that a smaller buffer size gives smaller delay through the codec which may be advantageous for contribution (conversational) links.

4. EXPERIMENTAL RESULTS

A range of experiments was performed which gave successive improvements in performance. The simplest system was one in which each sub-coder uses independent regulation and in which the law, relating (log) quantiser step size to buffer occupancy, is linear. (The log of the quantiser step size is often referred to as the 'transmission factor'.) Later experiments used dependent regulation, 'S-shape' regulation laws, and took particular precautions to prevent individual decoder buffer overflow.

4.1 Simple system

In the simplest system, regulation was performed individually for each sub-coder. The regulation law was linear, similar to that shown in Fig. 3 *(overleaf)*, and the sub-coder buffer size was limited to about 840 kbits which is equivalent to one frame at the nominal coded bit rate for an individual coder (140/6 Mbit/s). A new value of the transmission factor was calculated once per stripe. In this case, the quantisers for the different sub-coders showed large variations from stripe to stripe. This is unacceptable in terms of picture quality.

4.2 Simulating a single coder buffer

Variation from stripe to stripe was avoided by emulating a coder which had one large buffer rather than several individual buffers. The occupancy of this

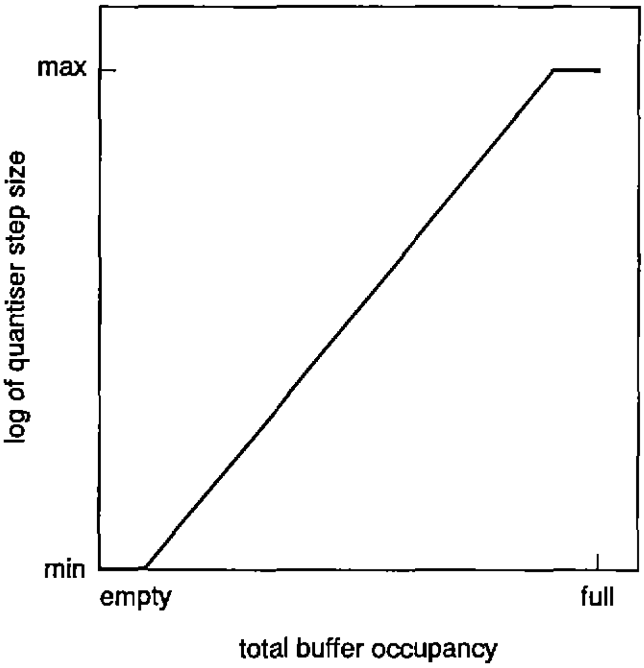

Fig. 3 - A linear regulation law.

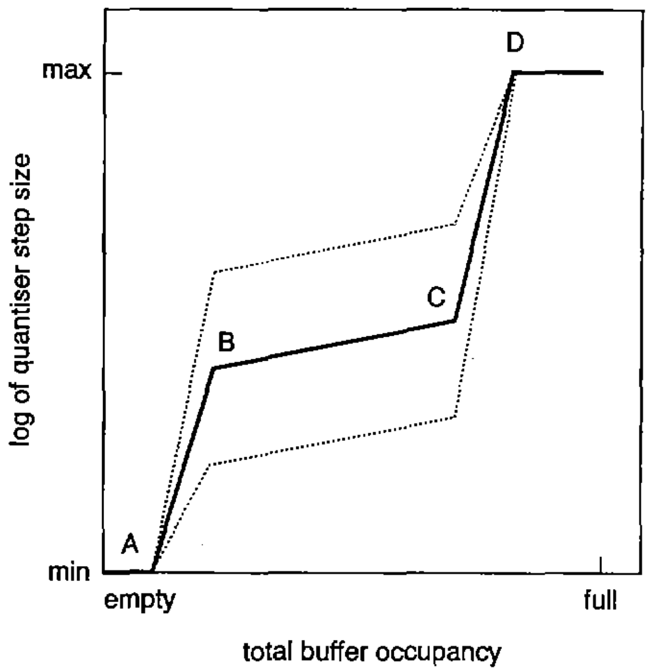

Fig. 4 - The 'S-shaped' law.

'single-buffer' was estimated by taking the sum or the total of individual coder buffer occupancies for the last six stripes. The quantiser step size then showed small variations from stripe to stripe but large variations across a field. These variations are caused by the field blanking period. During this time, coder buffers continue to empty but no data gets written into them by the VLCs. Consequently, at the start of a field the quantiser step size is finer than the optimum value for the whole field which is unnecessarily expensive in bit rate. The variation in quantiser step size across a field was removed by adding a correction term to the total buffer occupancy before calculation of the quantiser step size.

4.3 Field update

An alternative to field blanking interval correction is to update the quantiser step sizes once per field. Unfortunately, with the small coder buffer size that was chosen (in order to provide a wide margin in bit rate to prevent decoder buffer overflow), such a linear law is unstable, as the buffer occupancy varies dramatically from field to field. By increasing the coder buffer size, it was shown that field updating could provide a stable and effective regulation strategy. However, the field update approach has two major disadvantages compared with a stripe-based update strategy. These are:

- it requires a large coder buffer which leads to a large overall codec delay,
- it has a relatively slow shot change response.

4.4 An adaptive law

The optimum strategy, therefore, uses stripe-based update with field blanking interval correction of the total coder buffer occupancy; it is possible to improve the regulation further by employing an 'S-shaped' law such as the one shown in Fig. 4.

This regulation law is divided into three parts: AB, BC and CD. AB and CD are lower and upper 'fall-back' zones, where the quantiser step size changes rapidly to prevent buffer underflow and overflow respectively. The aim is that, within a picture, the regulation is operating over the shallow central region, BC, such that the quantisation step only varies by a small amount for possible large changes in buffer occupancy. This reduces the possibility of significant stripe-to-stripe variation of quantiser step size.

However, it is important that the law adapts, such that the central region of this regulation law covers the quantiser step size which is appropriate for the activity of the picture being coded. The law is adapted by first forming an integral of the total buffer occupancy 'error'. The error is defined as the difference between the current buffer occupancy and a reference buffer occupancy, which is typically set at 0.4 of the coder buffer size. The regulation law for the region BC is then calculated according to the following equation:

$$Log(quant.\ step\ size) = m.BO + c + \alpha.Integral$$

where BO is the total of the sub-coder buffer occupancies and m, c and α are constants.

The regions AB and CD are recalculated in order to avoid discontinuities in the law at the cusp points B and C. The integral term causes the law to translate vertically, as shown for example by the dotted curves in Fig. 4. This method of adaptation ensures that the central region covers the appropriate quantiser step size for the picture being coded. Both the slope, m, of the central portion and the 'integral gain', α, affect how rapidly the law adapts on a shot change, and also the standard deviation of transmission factor within a field.

With careful adjustment of m and α, it is possible to reduce the standard deviation of the transmission factor whilst maintaining a shot change performance comparable to that of the fixed linear law. Table 1 compares the standard deviation of the transmission factor for test patterns with a linear law and an optimised 'S-shaped' adaptive law. Both laws use the field blanking interval-corrected buffer occupancy, described in Section 4.2.

Table 1: Comparison of standard deviation of transmission factors for a linear and an 'S-shaped' law.

Sequence	s.d. linear law	s.d.'S-shaped' law
Moving Zone Plate	8.12	2.76
Multiple Zone Plates	3.5	1.16

The same laws were also compared for shot change performance (Colour Bars→Multiple Zone Plates). The ordinary linear law took 4 fields to stabilise completely, whilst the adaptive 'S-shaped' law took 6. Although the adaptive law took two fields longer to recover, there was no visible difference in performance.

Because the effective gradient of the 'S-shaped' law is much lower than that of a linear law it is also possible to use smaller coder buffers before instability sets in. The minimum coder buffer size that can be used before instability sets in, for the three approaches to buffer regulation discussed above, is shown in Table 2.

Table 2: A comparison of minimum coder buffer sizes for different regulation laws.

Law	Buffer size in Mbits	Buffer size in frames at the coded bit rate
Linear, stripe update	3.8	0.75
Linear, field update	9.0	1.76
'S-shaped', stripe update	2.7	0.54

The figures in Table 2 include 1 Mbit that must be reserved to take account of the fall in buffer occupancy during the field blanking period. If this is excluded and a comparison made over the 'active' buffer size, an 'S-shaped' regulation law can save about 40% in storage.

4.5 Buffer stuffing

Some form of bit stuffing is required in order to prevent sub-coder-buffer underflow on particular picture material. In initial experiments, the decision to stuff was taken on an individual sub-coder basis when an individual buffer occupancy dropped below a certain threshold. However, this could lead to inefficient use of bit rate for the following reason: since sub-coder buffers provide the same delay, regardless of their individual bit rates, all sub-coder buffers will underflow simultaneously when the coder delay, and thus the total coder buffer occupancy, drops to zero; therefore, provided the total buffer occupancy remains high, an individual sub-coder buffer occupancy can be free to fall very low, since this is merely a sign that its bit rate is low. Stuffing need only take place when the total coder buffer occupancy falls below a danger threshold.

5. DECODER BUFFER OVERFLOW

In the RACE HIVITS codec, if all of the picture information were to be concentrated in those stripes associated with a particular sub-coder, it would be possible for the whole of the available bit rate to be taken by that sub-coder. In this case, the associated sub-decoder buffer could overflow. This can be avoided by increasing the size of each sub-decoder buffer, or by applying limits to the individual bit rates at the coder.

In the steady state, it can be shown that:

$$r_i = \frac{BO_i}{\sum_{i=1}^{6} BO_i} R$$

where r_i is an individual sub-coder bit rate, BO_i is an individual sub-coder buffer occupancy and R is the total channel bit rate.

The maximum individual coder bit rate, r_i, is limited as shown above by the ratio of the maximum individual coder buffer occupancy, BO_i, and the minimum total coder buffer occupancy, ΣBO_i. The maximum value of BO_i is limited by quantiser control and the minimum value of ΣBO_i by setting the threshold for stuffing. By careful selection of these values, it is possible to restrict individual sub-coder bit rates to 'safe' levels.

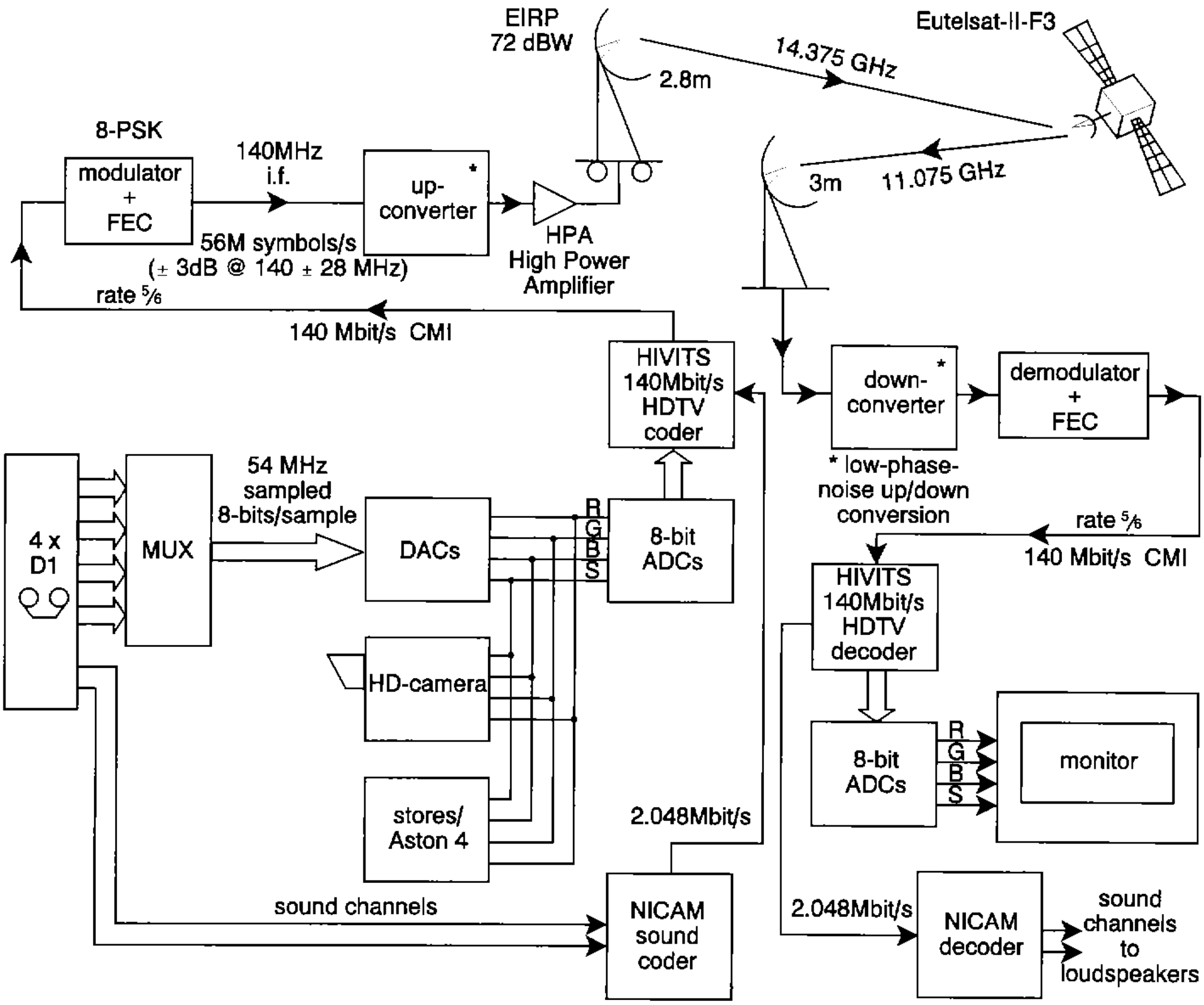

Fig. 5 - Block diagram showing the equipment used to provide an HDTV 'contribution' quality link via satellite to the MPEG meeting in London, November 1992.

In the current version of this equipment, an individual codec can take up to three times the nominal bit rate of each codec.

6. FIELD TRIALS

The HIVITS HD codec has already been tested and demonstrated live, on a number of occasions:

- WARC '92, Torremolinos, February 1992.
- The HIVITS project review days, BBC Kingswood Warren, May 1992.
- Tomorrow's World, a BBC science programme, October 1992.
- MPEG-2 meeting, London, November 1992.

The first of these demonstrations was over a satellite simulator; however, the remaining three demonstrations were over the Eutelsat-II-F3 satellite.

Fig. 5 shows a block diagram of the set-up used for the MPEG demonstrations. Here, the HIVITS codec was used to provide a 'transparent' link, which enabled the replay of previously-recorded HDTV computer simulation results from the BBC Research Department in Surrey, to the MPEG meeting at the BSI in central London.

The 140 Mbit/s output from the HD codec was carried over a 70 MHz satellite transponder using an 8-PSK satellite modem. The signal was up-linked at 14.375 GHz using a 2.8 m dish, and received at 11.075 GHz using a 3 m dish. The satellite data modem employed a rate 5/6 forward error correcting code and viterbi decoding.

With an up-link EIRP of 72 dBW, the E_b/N_0* was a little over 9 dB. With the modem's own error correcting code this was sufficient to keep the bit-error ratio from the demodulator within the limits of the HD codec's Reed-Solomon corrector.

Thus, with the equipment shown in Fig. 5, it was possible to provide a very high quality HDTV link to this rather difficult site.

7. CONCLUSIONS

A brief description has been given of a parallel implementation of a HDTV codec in which the bit rate is shared dynamically between the sub-codecs.

Coder time-base information was used to synchronise the decoder buffers rather than buffer occupancy data. Several buffer regulation strategies were investigated. An optimum regulation strategy involved stripe-based regulation, field blanking correction factors and an 'S-shaped' adaptive regulation law. Also, the performance of the regulation strategy worked well when constrained to avoid decoder buffer overflow problems. The parallel architecture of this codec is particularly suited to the implementation of future international HDTV contribution standards.

These solutions are not specific to the parallel processing approach that has been adopted for HDTV, but are equally applicable to multiple variable bit-rate video services operating within a single fixed bit-rate channel. A dynamic sharing of bit rate between the individual TV services can be achieved with the techniques described in order to maintain a constant quality across all services.

The HDTV equipment described was very successfully demonstrated on a number of occasions including tests via a satellite transponder.

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* Measured by the satellite modem.

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